KARELIA-AMMATTIKORKEAKOULU
Kone- ja tuotantotekniikan koulutusohjelma

Otto Karppanen

MODELING HEAT TRANSFER THROUGH A LOCK MECHANISM

Opinnäytetyö
Toukokuu 2014

THESIS
May 2014
Degree Programme in Mechanical Engineering
Karjalankatu 3
FI 80200 JOENSUU
FINLAND
Tel. +358 13 260 600

Author
Otto Karppanen

Title
Modeling Heat Transfer Through a Lock Mechanism

Commissioned by
Abloy Oy

Abstract

This case study compares the results of a heat transfer experiment performed in a laboratory with data from a simulation. Based on this experiment, it is apparent that simulating a heat transfer study can yield results which are comparable to those of a laboratory test.

The study was a quantitative analysis of the results of investigating the heat flow through a lock mechanism on an outer door of a low-energy building. In low-energy construction, heat transfer mechanisms are of great interest. In the case of the outer door, the lock mechanism is a major source of heat leakage. Lock manufacturer Abloy Oy commissioned this thesis to evaluate physics modeling as a technique for solving design problems related to heat transfer.

The results of this study indicate that software-based physics modeling of heat transfer analysis can compete with laboratory tests in accuracy of data. This simulation and virtual testing of designs can greatly reduce resource spending during product development.

Language
English

Pages 36
Appendices 1
Pages of Appendices 1

Keywords

heat transfer, thermodynamics, modeling

OPINNÄYTETYÖ
Toukokuu 2014
Kone- ja Tuotantotekniikan koulutusohjelma

Karjalankatu 3
80200 JOENSUU
puh. +358 13 260 600

Tekijä
Otto Karppanen

Nimeke
Lämmönjohtumisen Mallintaminen Lukkomekanismin Läpi

Toimeksiantaja
Abloy Oy

Tiivistelmä

Tässä opinnäytetyössä tutkittiin ohjelmistopohjaisen fysiikanmallinnuksen soveltuvuutta tuotesuunnitteluun. Analyysissä verrattiin fysiikanmallinnusohjelmiston tuottamia tuloksia laboratoriossa mitattuihin arvoihin. Tämän tapaustutkimuksen kohteena olivat Abloy Oy:n valmistaman ulko-oveen asennettavan lukkorungon lämpötekniset ominaisuudet.

Tutkimuksessa analysoitiin empiirisen kokeen ja simulaation yhteneväisyyksiä. Tutkimus osoittaa, että ohjelmistopohjainen lämmönjohtumisen analysointi tuottaa luotettavia tuloksia, ja mahdollistaa tuotteiden kehittämisen ja testaamisen virtuaaliympäristössä. Prototyyppien simulointi ja testaaminen voi tuoda huomattavia resurssisäästöjä tuotekehitykseen.

Huolella valmistellun fysiikanmallinnuksen avulla voidaan korvata empiirisiä kokeita ja nopeuttaa tuotekehitysprosessia.

Kieli englanti	Sivuja 36 Liitteet 1 Liitesivumäärä 1

Asiasanat
lämmön siirtyminen, lämmöneristys, mallintaminen

Table of Contents

1 Introduction

1.1 Background

The need to increase energy efficiency is a potent driving force in all aspects of engineering. The desire to get the most use out of the least resources has shaped every aspect of technological development since the industrial era [1]. Results of this approach are the characterizing properties of the modern world – miniaturization of technology, affordability of living and increase in the environmental sustainability of societies. Of particular interest to this thesis is the development of low-energy housing. This particular aspect of construction engineering has been very popular among environmentally conscious builders and engineers [2].

The quest for a house that needs a minimal amount of energy for heating has resulted in vast improvements in the heat insulation qualities of almost all parts that make up a house - except for the locks and handles. These parts require metal components in order to be reliable and structurally acceptable. Metal components are excellent conductors of heat and, conversely, cold. Finnish lock manufacturer Abloy Oy commissioned this thesis in order to research possible solutions to this problem of conduction.

Abloy Oy is a world-leading manufacturer of locks and locking systems, and the leading developer in door opening solutions. Abloy Oy is part of ASSA ABLOY group, a Sweden-based supplier of intelligent lock and security solutions. The company has a long history of innovative engineering and designs that are up to the highest standards of the day. Therefore it is natural that the company has held a keen interest in the development of engineering methods and practices. Finding out if virtual modeling is suitable for evaluating the thermal flows in a design is of great interest to the company.

Abloy Oy supplied the necessary parts and data for constructing both the virtual and the physical models. Some of the information about the lock mechanism and its materials is considered sensitive, and this has been accommodated in this thesis. Some of the withheld information may affect the replicability of this experiment, but the overall results should hold under diverse conditions.

The purpose of this thesis is to test if a virtual model of a lock mechanism can be made sufficiently accurate for the purpose of heat transfer modeling. The benefits and weaknesses of this approach to engineering by modeling are then discussed and analyzed.

1.2 Engineering by Modeling

The benefits of using virtual models for designing products and processes are numerous. Instead of building and preparing physical prototypes of the design and subjecting them to laboratory tests, the models can be tested virtually, using appropriate computer software for performing the calculations [3, p. 17]. This means forgoing the construction and testing of the prototype, saving time and materials. Some physical tests might require long, laborious and even dangerous laboratory experiments, which can be modeled easily and quickly in a virtual environment. This apparent saving of materials and time is naturally offset by the work needed to construct the virtual model itself, and by the time (and computer resources) needed to run the mathematically heavy simulations. Being able to compare these alternate resource expenditures at an early stage of the design process can facilitate great savings.

Sometimes, if the design is extremely simple and physically confined, an accurate model can be produced by using just the geometry of the design and known values of material properties. Often, however, it is necessary to produce at least one version of the design as an actual physical prototype, so that the behavior of the model can be verified. The behavior of a complicated physical system can sometimes be difficult to express as mathematical parameters in modeling software. The intricacies of physical interactions can be replaced by a simplified description of the model, as long as it has been verified through a laboratory test or some other physical measurement. In using these previous measurements in justifying the current model, the software is essentially being used not so much for testing the model as for testing the model´s behavior under some changes in its design. In most cases this is enough to give the engineer a good idea of what effects the changes would have on the design. It then requires separate judgment to determine when the design has evolved sufficiently to warrant the production and testing of a new prototype.

Investigating the feasibility of a computer model means that there are a huge number of physical variables available for comparison. In order to limit the extent of research, this thesis concentrates on a single case study experiment. The aim is to investigate the physical interactions involving a reasonably complex engineering design and a small number of physical parameters, and to perform the same tests in both a laboratory and a virtual modeling environment. The results are then compared quantitatively.

Both the physical and the virtual model are subjected to similar conditions in their respective environments. Then a set of measurements is obtained from both experiments, and their differences and similarities are analyzed. When comparing the results of the tests, a large part of the work lies in identifying the physical differences and limitations in the setups for each experiment [4], as well as in uncovering the possible sources of errors.

1.3 First-Principles Modeling and FEM

In the past, knowledge in engineering accumulated through experience, and designs evolved through iterative prototyping and physical tests. The main method for modern engineering work is modeling. Modeling involves creating a virtual design ranging from a free-body sketch (simple physical mockup whose behavior can be investigated by solving the related physics problems) all the way through to a detailed CAD (Computer Aided Design) model of the design and its surroundings with as accurate physical description of the design and its interactions with its surroundings as necessary. In order to investigate the physical interactions of a design and its environment, the system needs to be constrained so that the desired results can be solved.

Modeling can be used to investigate a multitude of physical actions between virtual designs. Modern modeling software is capable of analyzing almost any imaginable scenario, with virtual environments ranging from interactions between elementary particles to global weather systems [4]. All virtual designs are simplifications of their real-world counterparts, however, with the degree of simplification limited by the complexity of calculations.

The most commonly used modeling technique is finite element method (FEM), sometimes referred to as finite element analysis (FEA). In FEM, the design is constructed as mathematical formulae describing each physical interaction that would take place in the setup. To perform a calculation in FEM, the design is divided into smaller parts (elements), with each part represented by a set of element equations describing the problem. This subdivision is performed by numerical software. All the sets of element equations are subsequently approximated mathematically [5]. This method of physical problem-solving has the advantages of being able to represent complex geometries with varying material properties accurately, providing a good approximation as a result, all while describing a wide variety of physical systems across the design, for example heat transfer, fluid dynamics, mechanics, radiation, chemical reactions and so on.

Investigating physical interactions in a model means either having to define a formula describing the physical interactions inside the model, or using pre-existing parameters, such as empirical measurements or assumptions. When the physical quantities are calculated directly from the laws of physics, the process is called “first-principles modeling”. This method is the engineering extension of the first principles of formal logic. When computing a problem using first-principles analysis, the complexity of overall calculations becomes prohibitively large with increasingly miniaturized elements. Hence the structural subdivision has to be limited to a “good enough” level that produces a result that is accurate enough for the particular problem, and does it in such a way that further division would not give a meaningfully better result.

This thesis investigates the suitability of first-principles modeling of heat transfer to a design for a door lock and handle mechanism. Results from a physics modeling experiment performed on Comsol multiphysics software are compared to results from an actual physical experiment conducted in a laboratory.

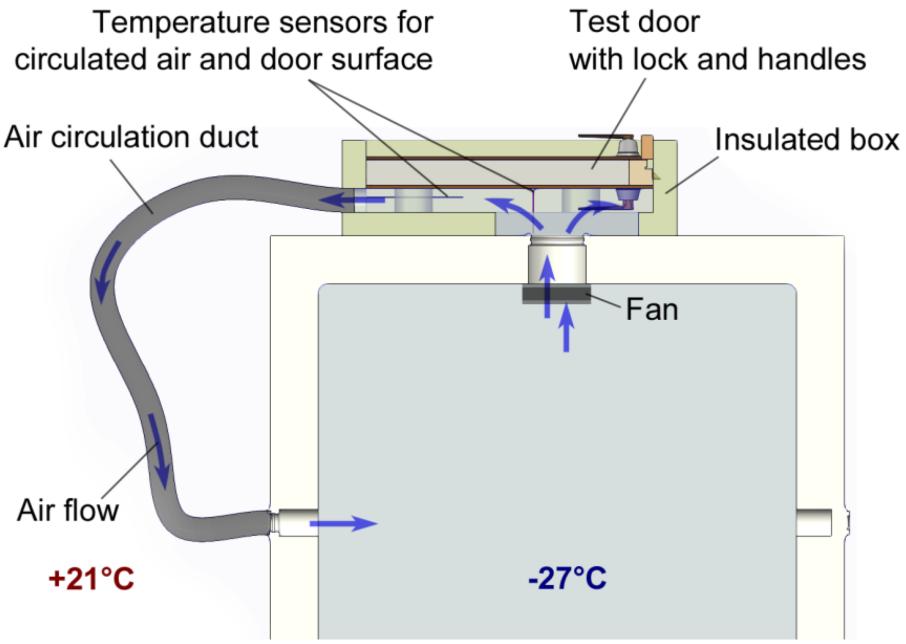
1.4 Experiment Design and Process

In order to investigate the capabilities of physical modeling, an experiment was set up in both a laboratory and a virtual environment. The experiment was used to determine the transfer of heat through a lock mechanism in the door of a low-energy building.

Defining the setup involved deciding which end results would be the quantities of interest and finding out which physical variables of the system affect the end results. It was decided that it would be interesting to determine the thermal insulation value through the lock mechanism and the door handle. These parts of the outer door of a low-energy building contain the most metal, and therefore contribute the most to heat transfer through the door. The environmental variables that determine the amount of heat transferred through the door are the air temperatures and pressures on both sides of the door, as well as the weather conditions, such as windiness. Humidity can also affect the results, but in order to keep the test setup simple, varying humidity values were not tested for.

By using a part of a door actually built for low-energy housing as a base ensured that the results of the experiment would be close to what could be measured in an actual low-energy house. A door manufacturer supplied the physical door for the experiment, as well as all the necessary information on the material properties of the door. The fact that a lot of the parameters of this setup were known beforehand enabled the accurate reproduction of the real world test in the virtual environment.

In a real-world situation, it was of greatest interest to both door and lock manufacturers to know what physical phenomena take place under the somewhat extreme conditions of Nordic winter. It was decided that the test setup should consist of a partial door with the lock and handle installed, with the outside temperature of -27°C and the inside temperature of +21°C. The difference in temperatures was created using a temperature-controlled cabinet. To better simulate exterior conditions, the outside of the door also had unrestricted airflow and a fan creating a constant turbulent airflow along the door´s surface (picture 1). The sides of the door were well insulated so as to minimize heat transfer around the area of interest.



Picture 1. The installation of the experiment on a temperature-controlled cabinet.

1.5 Structure of the Thesis

This thesis is divided into six chapters. Chapter one is an introductory chapter, with a short description of the experiment and its background. Chapter two contains a short account on the history of physics modeling, basic introduction to heat transfer as a physical concept, and some thoughts on the accuracy of physics models. Chapter three describes the experiment in detail. Chapter four compares the results of the physical and the virtual parts of the experiment. In chapter 4.3 there are two examples of testing improved designs with physics modeling software. Chapter five contains discussion on the feasibility of software-based modeling as a replacement for prototype-testing, based on carrying out this experiment. In chapter six, a short summary of the findings is presented.

2 Modeling in Engineering

2.1 History and Developments

To design a complex machine, system or process, an engineer needs to devise a plan or a sketch. When a plan, or a “design”, is finished, it makes sense to evaluate its feasibility by estimating it numerically. From the onset of the Renaissance era scientists have been researching the properties of physical systems, and studying the laws of physics in order to quantify them mathematically. This work on understanding the underlying reality of nature has brought mankind through the industrial and modern eras, all the way to the information era of today. As understanding of the laws of nature grew and the knowledge of physical properties of matter became more detailed, the engineers were able to calculate the workings of their design with increased accuracy.

Calculating the behavior of a complicated system requires a lot of effort. The utilization of computers to do the heavy calculations means that the complexity of the analyzed system can be increased in conjunction with the increasing calculating power of the computers. Today computers are capable of billions of calculations per second. This has lead to more complex modeling using more variables and more accurately modeled physics. In essence, by using the same time for doing the calculations, a faster computer can produce a more accurate result to the problem. This means, however, that an engineer must design the virtual experiment so that it does not become too complex and end up needing weeks of computing time.

The understanding of physical phenomena has greatly affected the way models are constructed. For example, thermodynamics as a natural science has advanced from phlogiston theory of the Renaissance era through the caloric theory of late 19th century all the way to modern thermodynamics. During this development the mathematical description of heat as a natural phenomenon has become increasingly accurate, eventually forming the basis of quantum theory and modern physics.

2.2 First-Principles Approach

Modeling means describing a problem mathematically. For example, the description can be a simple formula that depicts the phenomenon adequately for the situation, derived from experimental results and supported by measurements. When the description is based on established laws of physics, and not just empirical models or fitting parameters, it is called first-principles analysis.

The modeling of scientific problems involves relating some variables or parameters to each other using the established laws of physics. As the changing variables are made smaller, the description of events becomes more accurate and general. Differentially small rates of change of variables are represented mathematically by derivatives. When the variables are subjected into infinitesimal changes, the mathematically accurate description of the physical principles is in the form of differential equations. When the equations involve a derivative with respect to continuous variables, such as the temperature or pressure of a fluid, the general description of the problem is a partial differential equation (PDE). For a function $u(x_1, \dots, x_n)$ the PDE is of the form

$$F\left(x_1, \dots, x_n, u, \frac{\partial u}{\partial x_1}, \dots, \frac{\partial u}{\partial x_n}, \frac{\partial^2 u}{\partial x_1 \partial x_1}, \dots, \frac{\partial^2 u}{\partial x_1 \partial x_n}, \dots\right) = 0.$$

Modeling a heat transfer problem from first principles means that the functions that the PDEs are solved for are the functions described in the heat transfer theory.

2.3 Heat Transfer Theory

In physics, the definition of heat requires a lot of rigor as the description of a physical phenomenon becomes increasingly accurate. In engineering, it is satisfactory to define heat transfer as the flow of thermal energy from one object to another without work being done or matter being transferred. The heat transfer is always from the hotter object to the colder one.

Heat energy can be transferred by conduction, convection and radiation [5, p. 468]. Additionally, advection is transfer of heat by transporting a fluid that contains thermal energy. In this experiment advection is ignored, as the setup has only minimal fluid flows that would be capable of advection of heat. Conduction, convection and radiation are the effective methods for heat transfer in this experiment.

Conduction is the transfer of heat energy between substances as a result of their interaction. It can be shown [6], that the rate of heat conduction through a medium depends on the size and geometry of the object, its material properties, as well as the temperature difference across it. For a layer of thickness Δx, the rate of heat transfer $q_{conduction}$ is proportional to the difference of temperatures across the layer ΔT and the heat transfer area A, but inversely proportional to the layer thickness. For an infinitesimally small distance over a medium, this reduces to the differential form

$$q_{conduction} = -kA\frac{dT}{dx},$$

where the constant of proportionality k is the thermal conductivity of the material. The negative sign is added to the equation above to describe heat transfer as a positive value in the positive x-direction.

Energy transfer between a solid object and an adjacent moving fluid is called convection. In the special case where the fluid is still, the transfer of heat is essentially pure conduction. The movement of the fluid increases heat transfer between the solid and the fluid. The flow of a fluid can be created artificially by an external force (for example using a pump or a fan), or it can arise from the internal buoyancy forces that are induced by differences in the fluid density caused by variations in the temperature of the fluid. When the flow is due to an external force, the resulting convection is called *forced convection*, whereas convection involving internally generated flow is known as *natural convection*. [7]

The rate of convection heat transfer $q_{convection}$ is proportional to the temperature difference in the fluid and the area A through which the convection takes place:

$$q_{convection} = hA\Delta T,$$

where h is the convection heat transfer coefficient, ΔT is the difference between surface temperature and the temperature of the fluid suitably far from the surface. Due to the complex nature of convection, h is an experimentally determined parameter whose value varies according to geometry of the surface, the nature of the flow of the fluid, the fluids properties and the velocity of the flow.

Transfer of heat involving the change of phase of a fluid is also considered to be convection. Since phase transitions within this experimental setup are negligible, they can be disregarded as possible sources or sinks of heat energy.

In all bodies with a temperature above absolute zero, thermal motion of charged particles causes energy to be emitted in the form of electromagnetic waves. This radiation is called *thermal radiation*. The rate of heat energy $q_{radiation}$ transferred through thermal radiation is dependent on surface area A and temperatures of the surface T_s and the surroundings T_{surr}:

$$q_{radiation} = \varepsilon\sigma A(T_s^4 - T_{surr}^4),$$

where ε is the emissivity of the surface and σ is the *Stefan-Boltzmann constant*. Emissivity describes the surfaces capability to emit radiation, compared to a theoretical maximum. Temperatures of T_s and T_{surr} must be expressed in absolute value (Kelvins).

2.4 Accuracy and Predictability of Models and Measurements

In order to solve a problem, the physical phenomena within the problem have to be simplified through idealizations and approximations. This process is called model development [8]. It is important to identify all the variables that affect the problems solution, and to describe the interdependences between them.

During the development of the model, reasonable assumptions and approximations are used to make the model resemble its physical equivalent as accurately as possible. These guesses are inevitable sources of error. By formulating the physical laws and principles mathematically, the formulas can be used to evaluate the effect of erroneous guesses on the results. If the mathematical model produces results that are not consistent with the real world model, it means that the mathematical model is too crude, or that some of the original guesses need to be replaced by more sophisticated assumptions.

The model can only be as accurate as the guesses made in building it. This also means that the solution obtained with the model probably will not be accurate under conditions where the initial approximations do not hold.

Model development is done using appropriate software packages. While the software has the capacity to form and solve the PDEs describing the problem mathematically, it is the engineer’s task to assess the necessary physical variables and laws needed to describe the problem.

Errors in results can arise systematically or randomly [9]. Systematical errors are often the result of imperfect measurements or faulty calibration of instruments. Inaccuracies in the approximations of the initial conditions are another source of systematic errors, as are changing conditions during the experiment. Random errors arise through unpredictable fluctuations in measured readings, through imperfect methods for recording the observations or through unexpected interference from an external factor.

In this experiment, systematical errors have been minimized by using multiple different measurement devices for temperatures. Random errors have been addressed by doing the measurements carefully and by using averaging techniques in determining the data values.

3 Arrangements for the Physical and Virtual Experiments

3.1 Laboratory Experiment Setup and Instruments

The physical setup was constructed in a laboratory at the Karelia University of Applied Sciences. The construction was devised in several meetings with teachers, engineers from Abloy Oy and experts in thermodynamic testing. The construction was performed on site at the laboratory.

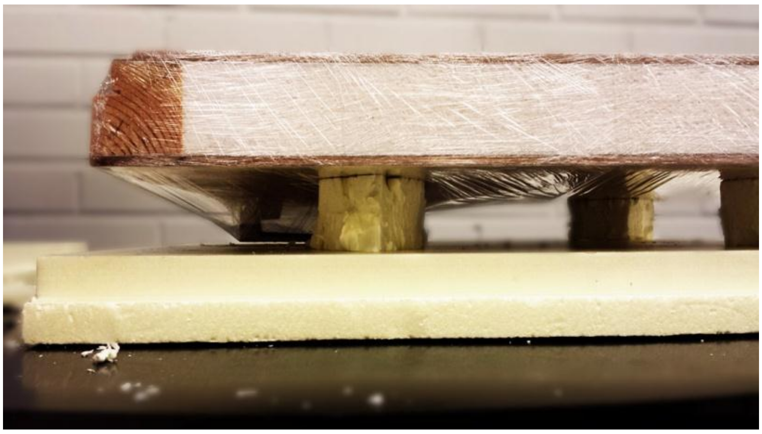
As a basis for the experiment, a 60cm by 60cm piece of well-insulated door was provided by Edux-Ovet Oy, a Finnish manufacturer of doors. The sample was a 65mm thick part of an outside door, and the manufacturer reported its U-value as less than 1.4W/m^{2}K. The sample had been prepared for installation by machining in the slot and holes for lock and handles (picture 2).

Picture 2. The door frame with pre-drilled slots for lock and handles.

The lock case provided by Abloy Oy was model LC102, which is a very popular lock in the Finnish market area. Abloy Oy also provided the handles and all the parts required to complete the installation of the lock and handle mechanisms (picture 3). The lock case is a relatively complicated mechanism with multiple parts that have varying material properties, information of which is not publicly available. The handles provided were of model Forum, produced by Abloy Oy.

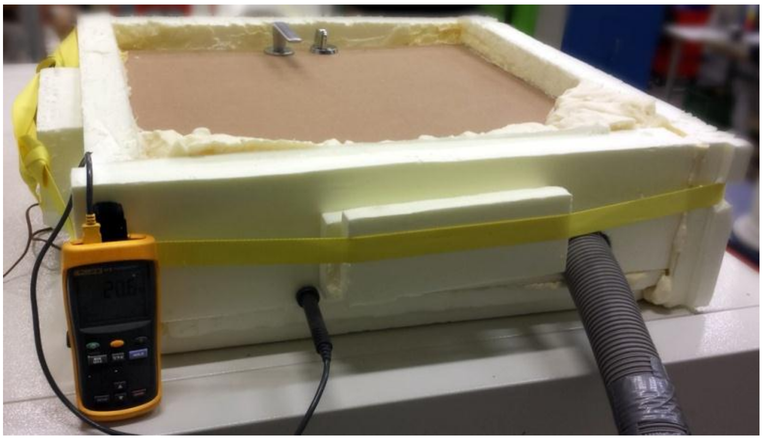
Picture 3. Lock and handle parts for the laboratory experiment.

The door was installed horizontally, supported on three pieces of 50mm thick insulation foam (picture 4). The supports were positioned a suitable distance away from the handles so as to minimize their interference with heat flows near the area of interest. Cling wrap was used to protect the door surfaces during construction.



Picture 4. Constructing air circulation and insulation.

In order to isolate the test door from heat sources in its surrounding environment, an insulating frame was constructed (picture 5). Finnfoam FL-300 insulation boards of 50mm thickness were used for the frame, and the construction was made airtight using Sikaflex^{TM} construction foam.



Picture 5. Insulated box with air circulation duct and airflow thermometer.

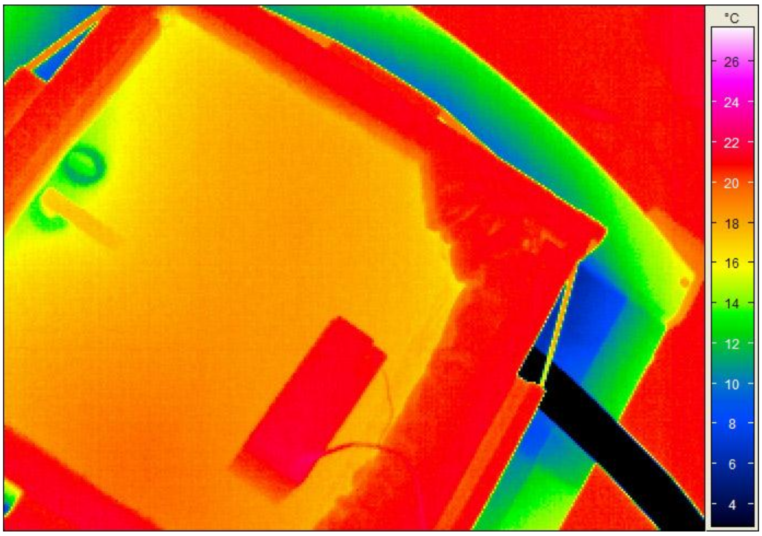
Holes were prepared in the insulating frame so as to facilitate the cooling airflow. From the insulated box, the cooling air was circulated back into the temperature-controlled cabinet using an industrial air duct, reducing the cooling load on the cabinet. The cooling airflow was produced by a 100mm diameter 12V computer case fan installed on the top vent of the cabinet. Using a fan to produce the airflow ensured that the airflow on the door´s lower surface was constant and turbulent.

To measure the cooled down temperature inside the insulated box, two temperature sensors were installed in the box; one to measure the surface temperature of the door and one to measure the temperature of the air circulating in the box. An additional data logging device was used to provide a secondary temperature reading for increased confidence in the measured data.

On the top side, the door and handle were painted matte black using spray paint (picture 6). This was done so as to give the observed surfaces an even value for effective emissivity. The varying materials of the wooden door and metal handles and lock components have distinctive values for surface heat emissivity, and it is very hard to determine their surface temperatures from measurements of their radiative properties without knowing those values accurately. To make measuring the thermal radiation easier, the surfaces were painted over with a paint whose emissivity is known. The layer of paint had to be kept thin so that it does not interfere with the thermal conductivity or surface convection properties significantly. In addition, a block of wood was used to act as the door´s counterpiece in the frame.

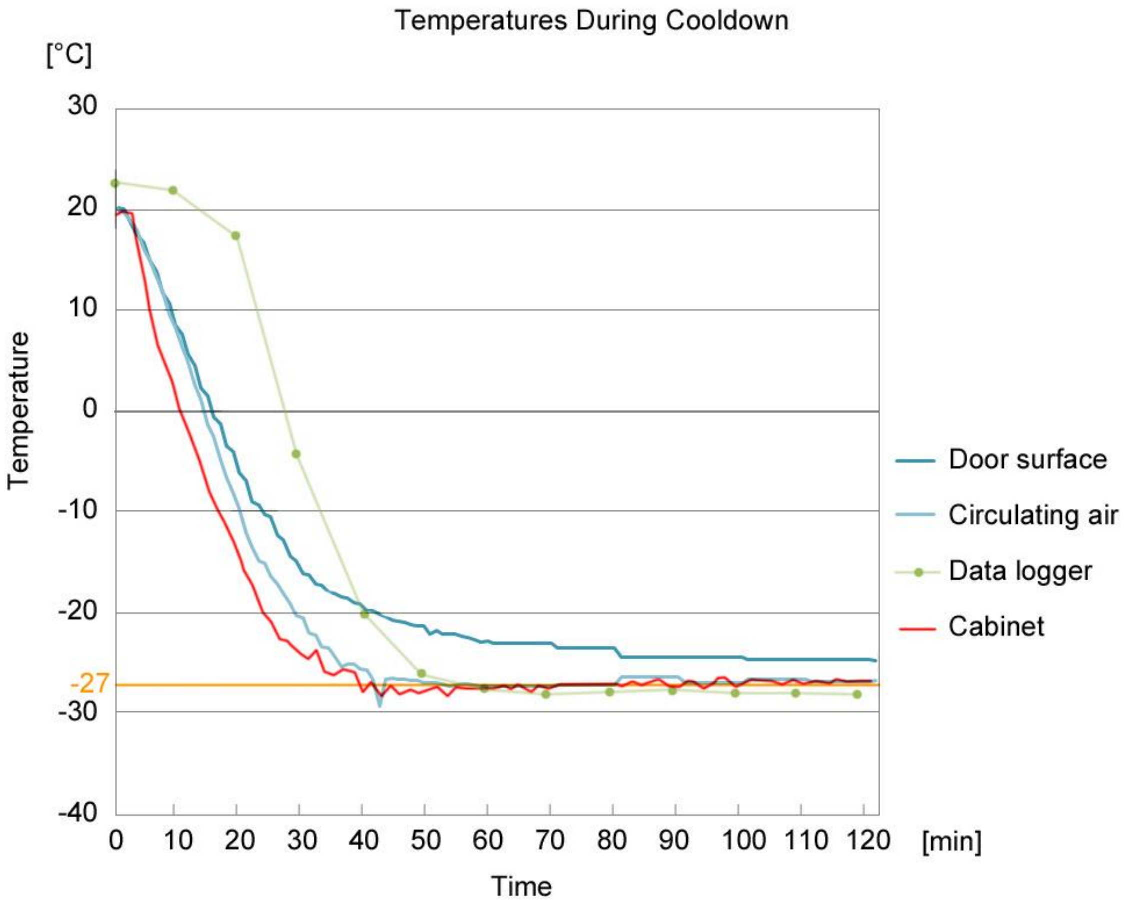
Picture 6. Surfaces were painted black to provide even surface emissivity.

In this experiment, the thermal difference between the inside and outside air is kept up artificially. The heat flow through the tested door frame produces a thermal equilibrium pattern on the surface of the door. This pattern is dependent on the varying thermal properties of the constituent parts of the door frame and lock system. An infrared-sensitive camera was used to capture an image (a thermogram) of the pattern on the surface for analyzing the surface temperatures (picture 7). Additionally, surface temperatures of designated points were measured using a handheld laser scanner.



Picture 7. Thermogram of the experiment setup.

The experiment was started at the room temperature of the laboratory (+21°C). The inside of the temperature-controlled cabinet was cooled down relatively quickly (approximately 1°C/minute), and the forced airflow provided by the fan conveyed the cooled air to the experiment. This cooling was monitored by comparing the measurements of the installed temperature sensors with the cabinet's internal sensor readings (graph 1). The measurements for the cabinet and surface temperatures were made once a minute, and the additional temperature measurements using the TinyTag –data loggers were taken every 10 minutes.



Graph 1. Temperature measurements during the first 120 minutes of the experiment.

In order to provide realistic data for simulated weather conditions, the heat flows across the setup had to be given time to reach an equilibrium. During the physical test it was observed that it took the various sensors approximately four hours to reach a stable state where their temperatures no longer changed significantly over time. These measurements at the four-hour mark were used as the final results of the physical cool-down experiment.

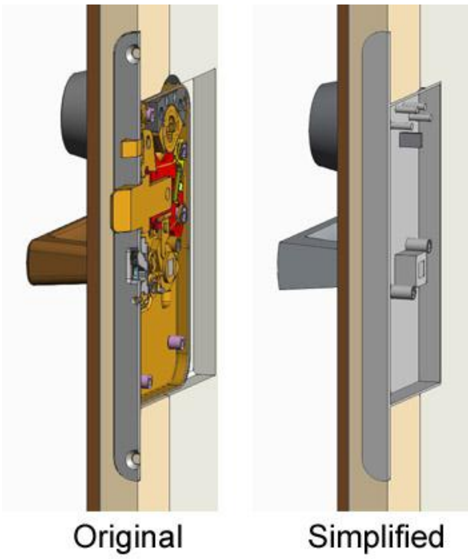
In the laboratory experiment, the instruments used (Appendix A) were provided by Karelia UAS. Some of the instruments had been calibrated and tested beforehand, and others were tested to be within manufacturers' specifications afterwards. The measurements provided by the various instruments coincided well with each other, thereby increasing confidence in the results.

3.2 Virtual Model and Quantities of Interest

This chapter explains the construction of the virtual model, followed by the description of the modeled physics. Within the construction of the model, the validity of the model is discussed. In the end of the chapter, the quantities of interest are explicated.

The model used in the experiment was built using PTC Creo 2.0 –software. Abloy Oy provided the complete and accurate 3D-models for all the parts used in the lock mechanism and handles. The door sample was modeled based on measurements done in the laboratory, and on information provided by Edux-Ovet Oy. All the parts were combined into a single virtual assembly.

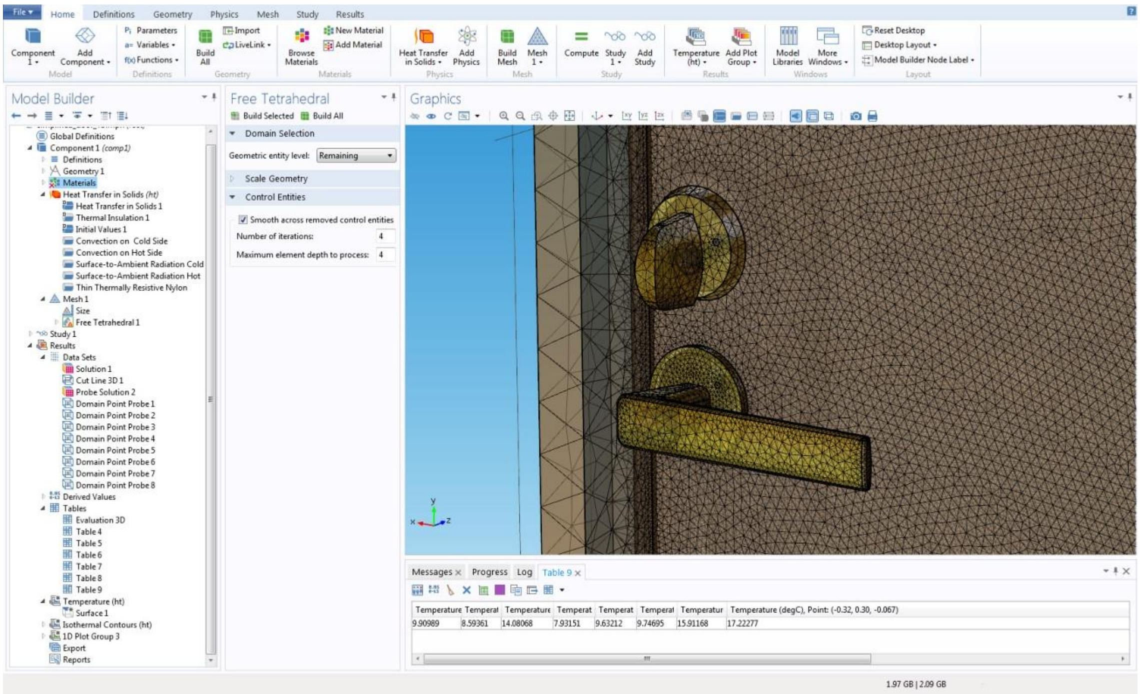
The lock mechanism and its surroundings constitute a relatively complicated system. To describe all the parts and their interactions in detail would have required the solving of a vast amount of partial differential equations, and would have taken a very long time. To bring down the time needed for calculations, the model had to be simplified a great deal (picture 8). By making the model as simple as possible, and then gradually adding complexity to it and solving it, a level of complexity was arrived at where the model describes the physical events quite accurately while being computable in a reasonable time.



Picture 8. Simplified geometry for decreasing computation time.

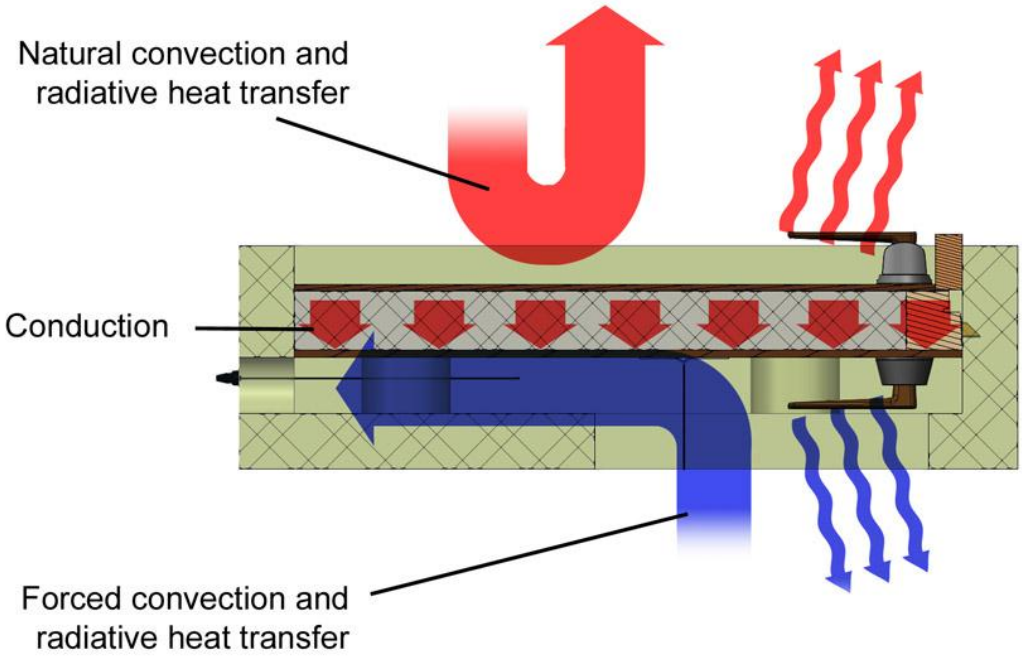
The model was simplified in almost all aspects. The geometry of the model lost a lot of its complexity, as complicated mechanisms were replaced by crude geometrical forms. For heat transfer studies, the geometry does not have to be subdivided too finely because heat flow through a homogenous material does not benefit from added resolution, and adding resolution to the mesh would only slow down the computation. Material properties of parts lost their intricacies as parts could not be described realistically. For example, the thermodynamical properties of a chrome-plated brass alloy which has received a coat of paint are very difficult to locate in literature, and had to be based on educated guesses. All in all, a lot of compromises were made, but the end result did still retain most of the thermodynamically important properties with relative accuracy; namely the masses of the objects, their overall heat transfer capacity and the general geometry of the objects. Some objects were replaced entirely by mathematical descriptions of heat flow through an equivalent geometry and material properties.

The final model was imported as geometrical objects into Comsol 4.4 (picture 9), a multiphysics simulation software. Within this software, the physics involved in the test were described, their relation to the geometry of the objects was explicated, and the end result of the physical events was calculated. Since the model does not contain time-dependent variables, the problem can be solved using stationary approach.



Picture 9. Comsol 4.4 Multiphysics user interface.

To describe the heat flows in the experiment, the relevant physics were described in the model. The software's internal module for calculating heat transfer in solids was used. Since opaque solids can only transfer heat by conduction, whereas fluids transfer heat by convection and radiation [7, p. 34], these heat transfer mechanisms were allocated to the proper mediums in the model. Convective heat transfer was calculated for all surfaces of the model that were adjacent to air. The convection on the cooled side of the door was described as external forced convection with an average airflow velocity of 0.5m/s (this was an approximation based on the fan specifications and the internal dimensions of the insulated box). Convection on the top side of the model was described as natural convection on top of a horizontal plane. On the cooled side, as well as on the warm side, surface-to-ambient radiation was calculated for all surfaces (picture 10). Inside the objects the heat flow was produced by conduction within the materials and across material boundaries.



Picture 10. Different heat transfer mechanisms are in effect in different parts of the setup.

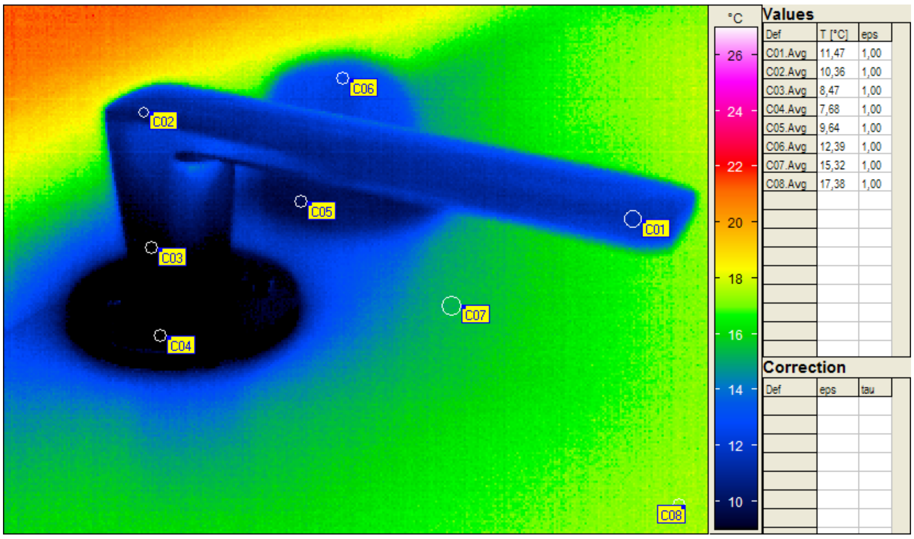
Due to the relatively well sealed construction and small size of interior spaces in the lock mechanism, the amount of heat transfer through internal convection was judged to be so small as to be ignored. The insulating box surrounding the door was replaced in the model by non-conductive contact surfaces, meaning that no heat flowed through those surfaces.

Solving the heat flow equations throughout the model produced detailed information on the thermal conditions at the model´s surface. These values could then be mapped in an image for comparison with the infrared images from the laboratory experiment. The total heat flow through the door and lock system could also be evaluated, and this result could be used in the future for comparison between new and old versions of the design.

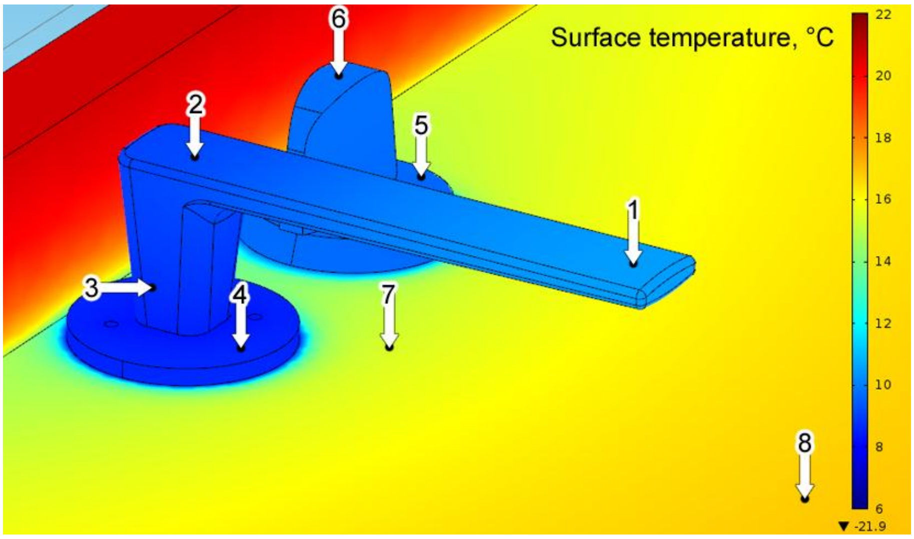
4 Compatibility of the Real and Virtual Models

4.1 Test Result Comparison

In order to compare the virtual tests results with those of the laboratory test, the surface temperatures of the model were evaluated at the same spots as they were measured in the laboratory. Temperatures in the laboratory were obtained by using a laser scanner and by reading the infrared image data. The numbered measurement points are marked in the pictures below.



Picture 11. IR-camera thermogram. Temperatures measured from marked circular regions.



Picture 12. Measurement points for modeled values.

It should be noted that the colors indicating surface temperatures are represented in slightly differing palette in each image. The values measured in the infrared image were averages of small circular areas in the image. This reduces noise in the data and makes the values obtained considerably more reliable. Temperature measurements of each point in their corresponding environments can be found in the table below.

Table 1. Comparing the modeled and measured surface temperatures:

Point #	Laser scanner [°C]	Infrared image [°C]	Modeled data [°C]
1	10.9	11.5	10.4
2	8.9	10.4	9.1
3	8.7	8.5	8.4
4	8.2	7.7	7.9
5	9.8	9.6	9.7
6	12.4	12.4	10.1
7	15.0	15.3	15.9
8	17.5	17.4	17.2

Measurements and modeled data can be seen to agree quite convincingly. The largest deviation from the measured values is at point #6, which is located on top of the lock release switch. This spot is not in the immediate vicinity of the areas of interest, and is therefore oversimplified in geometry. This in turn has resulted in the simulation producing a slightly inaccurate result for this particular spot.

4.2 Analysis of the Results

Considering the amount of simplifications made to the virtual model, the results agree well with those of the laboratory test. Most of the modeled data is within ±1°C of the measured values.

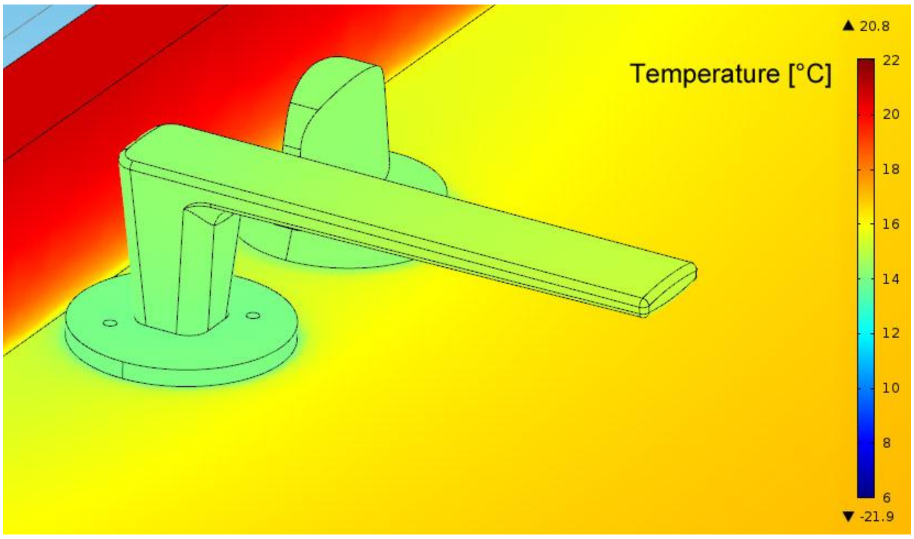
Possible sources for the slight deviation in measurements are numerous in both laboratory and software-based results. The position of each measurement point varied slightly from one environment to another. Variation in physically measured temperature can be the result of measuring technique, instrumental variation or changes in the environment. In the modeled data, additional inaccuracies could rise from imprecise material data, insufficiently defined starting parameters or from oversimplifying the geometry.

It is apparent that the temperature measurements of painted metal surfaces contain the largest deviation from the modeled results. This is most likely because the material properties of their constituent alloys were inaccurately defined in the model, and because the thin paint layer was not completely able to homogenize the surface emissivity. Also, the contacts between metal parts of the virtual model were described as touching each other, whereas in the laboratory test the parts would have gaps between them. The parts in a real lock mechanism are separated by thin layers of oil, air, dirt or oxidized metal, and all these extra layers interfere with the heat flow through them. These effects accumulate through the structure, and their overall effects of the model are difficult to predict.

The test only involved the modeling of heat transfer through the system, since that was the area of interest in this study. Adding other aspects of physics to the simulation, such as structural testing and thermal expansion might change the results slightly.

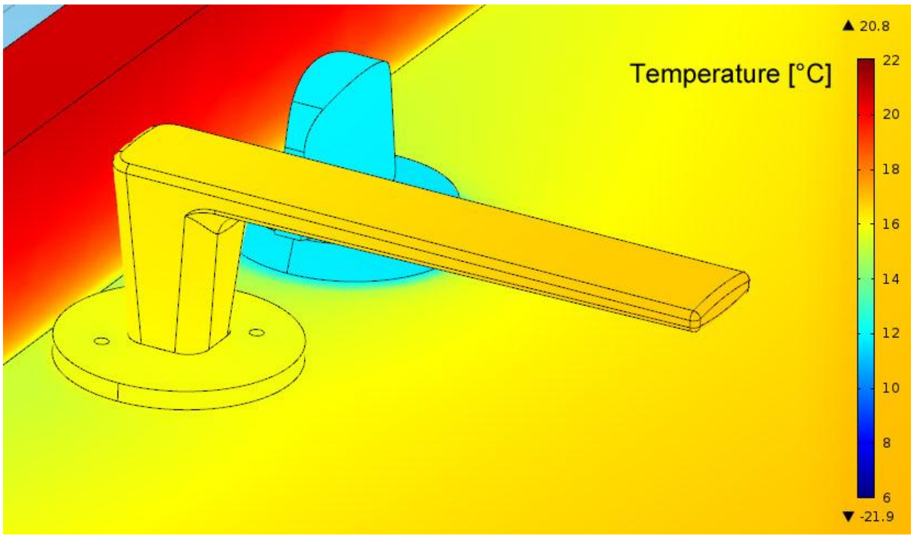
4.3 Simulating Improved designs

Modifications to the design were tested in the virtual environment. The heat transfer through the whole lock mechanism is the main quantity of interest in this experiment. It can be affected easily by replacing materials within the model with ones that conduct heat less readily. For example, replacing all the structural steel parts of the model with similar parts made of stainless steel, the heat transfer through the structure can be reduced dramatically (picture 13). This means replacing all the screws and casings as well, and so would not be a practical approach. The outcome clearly shows that it is something that could be taken into account when considering improvements to the design´s material composition.



Picture 13. Changing the composition of steel parts to stainless steel changes the resulting surface temperatures considerably.

The largest heat transfer conduits are the solid metal shaft connecting the handles and the lock release rotation shaft. Replacing these with plastic parts is structurally unacceptable, but will give an approximate idea of what can be achieved in the thermodynamical properties, if suitable materials were available. In this test (picture 14), the screws holding the mechanism in place were left unaltered in order to examine their contribution to the heat flow.



Picture 14. Replacing the most conductive parts with plastic can have a strong effect on the conductivity.

From this result it is clear that the screws holding the lock release mechanism contribute far more to the heat transfer than the connecting shaft. For the handles, the connecting shaft is the major heat transfer conduit.

Each of these tests took about an hour to compute, so it is clear that this method of simulated testing makes the physics testing of designs very easy and affordable. Trying out new ideas for the design instantly, without the need for a prototype and a laboratory experiment, can accelerate the whole engineering process considerably.

5 Discussion and Conclusions

It seems that physics modeling from first principles is a valid approach to verifying the model´s heat transfer properties for this lock mechanism. For this particular heat transfer study, the simulation produced results that were encouragingly close to laboratory measurements.

This method of testing designs in simulated physics environment does, however, bring with it a need for additional caution regarding validity of parameters used in the model. Physical properties assigned to the design have to be well known and comprehensively accounted for in the model. For example, small errors in material properties can lead to unexpected or misleading results in heat transfer studies.

Building an accurate model of a design in a physics modeling software can be laborious and even difficult. Preparing a good model for physics software requires very accurate knowledge of the geometry and the material properties of the model. Some of this information can be replaced by simplifications, which, in turn, can be validated with actual physical tests on a prototype. Once that model is ready, however, further development and testing becomes relatively easy. Performing tests on existing models can streamline their design process by eliminating or reducing the need for a prototyping phase. With increasing computational power, the models can be subjected to more accurate and rigorous testing and more complex models can be resolved in less time.

In the case of the lock mechanism, and presumably in other cases of comparable complexity, the early phases of the design process should include the evaluation for the need of testing the physical properties of the model. In that evaluation, it is reasonable to weigh the benefits of building and testing a prototype against a virtual test of a virtual model. Sometimes it may be advantageous to build a partial prototype, if the quantities of interest in the model are limited to a small section of the model, or to build a full prototype but only a partial virtual model.

The benefits from modeling the design virtually are always dependent on the design parameters, and need to be estimated individually for each design. In the case of the lock mechanism of this thesis, the benefits can be evaluated, for example by roughly comparing the time and resources taken by each, a simulation of a virtual model, and a laboratory test of a prototype. In essence, both tests build up on existing knowledge, in that they use the experience from previous designs as a starting point. Both tests require time to set up, the virtual model needs parameters and material properties inserted into it, and the laboratory experiment needs to be constructed and set up.

The equipment is costly in both experiments, but the price of a computer and the necessary software, while not insignificant, is a fraction of the price of the laboratory equipment and instruments. However, the equipment can be hired or the tests can be performed by specialist labs, so all the costs of the experiment should be evaluated case by case. All in all, it is no simple task to estimate the starting costs of an experiment. In this particular experiment, however, the virtual testing environment does represent an extremely affordable alternative.

Running the tests also takes time and resources. The laboratory experiments took four hours to perform, whereas the simulation produced its result after about one hour of processing. If another test was to be performed with different parameters, the laboratory environment would need to be acclimatized for several hours and then the test would have to be set up again; the simulation would require only the change of the parameter, and it would be ready for another run. In essence, the laboratory experiment could be performed once a day, whereas the simulation could be programmed to run once every hour, with different parameters.

The setup of the experiment required the production of stable conditions in the laboratory, simulating cold Nordic winter. This meant using a robust industrial climate-controlled cabinet, which consumed a lot of energy during operation. The computer running the virtual experiment used a fraction of that energy to simulate the same conditions.

In conclusion, it seems reasonable to assume that in developing the model tested in this experiment further, physics modeling software can be used instead of physical prototypes. However, it should be noted, that in this test only heat transfer was modeled mathematically, and that other aspects of physics modeling would need to be integrated in order to add rigor to the model.

6 Summary

In this thesis it has been shown that modeling a heat transfer problem using physics modeling software and FEM produces results that agree with the results of a laboratory experiment using the same parameters. It seems that a relatively crude model is enough to produce adequate results, as long as all the thermodynamically relevant details are accounted for.

When the development of a product reaches testing phase, it can be very useful to evaluate the benefits of performing the tests in a simulation instead of building a prototype. Utilization of simulation for testing designs can significantly accelerate product development as it facilitates rapid testing of new ideas.

Bibliography

[1] Schulze, Peter 1996. Engineering Within Ecological Constraints. Washington DC, USA: National Academies Press. ISBN:9780309051989

[2] Habermann, Karl J. 2012. Energy-Efficient Architecture : Basics for Planning and Construction. Basel, Switzerland: Birkhaeuser. ISBN:9783764372538

[3] Herrera, Ismael 2012. Mathematical Modeling in Science and Engineering : An Axiomatic Approach. NJ, USA: Wiley. ISBN:9781118087572

[4] Pryor, Roger W. 2012. Multiphysics Modeling Using COMSOL V.4. Canada: Mercury Learning & Information. ISBN:0763779997

[5] Rao, S. S. 2004. Finite Element Method in Engineering (4th edition). MA, USA: Butterworth-Heinemann. ISBN:9780750678285

[6] Fourier, J. 1822. Théorie analytique de la chaleur. Paris: F. Didot

[7] Cengel, Yunus A. 1998. Heat Transfer A Practical Approach. USA: McGraw-Hill. ISBN: 9780070115057

[8] Nikrityuk, Petr A. 2011. Computational Thermo-Fluid Dynamics : In Material Science and Engineering (2nd Edition). USA: Wiley-VCH. ISBN:9783527331017

[9] Rabinovich, Semyon G. 2006. Measurement Errors and Uncertainties: Theory and Practice. NY, USA: Springer. ISBN:9780387253689

This appendix contains information on the instruments used for the measurements.

	Instrument	Used for	Accuracy
	Microscanner™ D501-RS	Surface temperature measurements	± 1 %
	Weiss WK11-1000	Cooling the experiment	± 1°C
	Fluke 51 II	Temperature measurements of the airflow and the surface sensor	± 0.3°C
	JenOptik Variocam	Infrared photography	± 0.3°C
	TinyTag data logger	Cold air temperature measurements	± 0.4°C

More information about manufacturers and specifications available at:

Microscanner:

http://www.exergen.com/industrial/specs/D-Series.html

Weiss WK-11:

http://www.weiss.info/

Fluke 51 II:

http://en-us.fluke.com/products/thermometers/fluke-51-ii-thermometer.html?fbid=DcY51FrtS5-

JenOptik Variocam:

http://www.infratec.de/

TinyTag data logger:

http://www.geminidataloggers.com/